A Catalog of Porosity and Permeability from Core Plugs in Siliciclastic Rocks

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Abstract

Porosity and permeability measurements on cored samples from siliciclastic formations are presented for 70 data sets, taken from published data and descriptions. Data sets generally represent specific formations, usually from a limited number of wells. Each data set is represented by a written summary, a plot of permeability versus porosity, and a digital file of the data. The summaries include a publication reference, the geologic age of the formation, location, well names, depth range, various geologic descriptions, and core measurement conditions. Attributes such as grain size or depositional environment are identified by symbols on the plots. An index lists the authors and date, geologic age, formation name, sandstone classification, location, basin or structural province, and field name.

Introduction

Porosity and permeability measurements are frequently made on plugs extracted from core from wells drilled for oil and gas exploration. The data are valuable for linking permeability, a quantity not directly measured with well logs, to porosity, a quantity which is routinely determined with well logs. The definitions of porosity and permeability and methods of laboratory measurement can be found in such references as American Petroleum Institute (1956, 1960), Bass (1987), Dullien (1979), and Hearst and others (2000).

This report presents a catalog of porosity and permeability data, along with geological and location information, taken from sources in the open literature. The compilation is restricted to measurements on core plugs in conglomerates, sandstones, siltstones, and shales. An explorationist may want to select an analog from the catalog in order to infer the permeability and porosity of a particular reservoir of interest. The catalog can also be used for general studies of porosity and permeability in the subsurface.

For this compilation, the ideal data set has the following attributes: (1) a minimum of 20 values spanning a range of porosity and permeability, (2) core plugs sampling a specific geologic formation, preferably from a small number of wells, (3) a referenceable source, (4) formation name, age of formation, depth, and location, (5) a description of the depositional setting, (6) petrological description including grain size, primary minerals, and diagenetic minerals, and (7) method of measurement. The presence of hydrocarbons was not a criterion.

Few data sets met all these criteria. Permeability and porosity data are found in the geological, petrophysical, and petroleum engineering literature. The supportive descriptions of the samples vary greatly according to the nature of the study being reported. Different papers variously report grain size and sorting, sandstone classification, facies classification, lithology, clay content, or depositional environment. Petrological observations may be reported at length or not at all. Some authors focus on reservoir quality, and porosity and permeability are discussed at length. In other papers, porosity and permeability data are presented with little explanation. Data sets were included in this catalog if sufficient information was provided to give a geological context for the data. A simple listing or plot of porosity and permeability data and a location was not sufficient. A few papers gave average values rather than values from individual samples; these data were included if the accompanying geological descriptors rendered the data of particular interest.

The Indexes

Table 1 lists the data set number, authors and date, geologic age, formation name, location, basin or structural province, and field. Table 2 lists the data set number, authors and date, sandstone classification, the maximum porosity and permeability, and yes/no (Y/N) indicators for grain size, sorting, primary mineralization, secondary mineralization, depositional environment, facies, thin section porosity, and vitrinite reflectance. A "Y' indicates that a particular data set has information for that attribute. For example, "Y" in the grain size column indicates that each value of porosity and permeability also has a grain size value. An attribute such as grain size or facies is tabulated in the spreadsheet for that data set and may or may not be represented by symbols on the plot for that data set.

A spreadsheet named Index.xls contains the same information as Tables 1 and 2, so that a user can sort on any of the Y/N attribute fields in the worksheet version of the Index, to find all data sets which have, for example, grain size or depositional environment values assigned to either individual data points or groups of data points. The user can also sort on maximum permeability to find all the low-permeability data sets, and by inspecting the location and age columns, can then find (for example) data for tight gas sandstones in Rocky Mountain basins.

Data Acquisition and Conventions

Permeability and porosity values were obtained from either tables or figures in published reports and papers. Figures were expanded on a copying machine and digitized in accordance with the scales on the figures. A plot of the digitized points was then compared to the original. Accuracy varies according to the scale and quality of the original plot.

Permeability values posted at 0.1, 0.01, or 0.001 millidarcy may represent the lower limit of measurement rather than true values. For example, if six or seven data points are clustered at 0.001 md and varying values of porosity, with no permeability values less than 0.001, then one can assume that 0.001 md is the lower limit of permeability measurement. Similarly, if six or seven data points are clustered at 10,000 md and there are no higher permeability values, then it is assumed that 10,000 md was the upper limit of measurement.

Many authors do not report the method of determining porosity and permeability. Where no method is stated, it is reasonable to assume that standard procedures (American Petroleum Institute (1956, 1960)), often referred to as "routine core analysis" methods were used. A plug, typically one inch in length and ¾ inches in diameter, is cut orthogonal to the long axis of the core. Water and hydrocarbons are extracted from the plug with heat and solvents. Porosity is determined using a Boyles law method, in which helium invades the evacuated sample. Permeability is determined by flowing air along the long axis of the plug, thereby obtaining the horizontal component of permeability if the well was drilled vertically. Samples are assumed to be unconfined or confined at very low pressure ("ambient conditions") unless it is stated that measurements were carried out with the samples confined and subjected to an elevated pressure ("in-situ conditions").

Grain size is specified for many of the data sets in this catalog. Grain size divisions are logarithmic, based upon doublings of grain diameter (Table 3). The phi unit is the exponent in the relationship: grain diameter = 2**(-phi). For example, grain size of a coarse sand ranges between 1.0 and 0.5 mm and the phi value ranges between 0 and 1.

Table 3. Grain size classification, after Table 3-2 of Pettijohn and others, 1973.

Class	phi units		diameter, mm	
	upper	lower	upper	lower
very coarse sand	-1	0	2	1
coarse sand	0	1	1	1/2
medium sand	1	2	1/2	1/4
fine sand	2	3	1/4	1/8
very fine sand	3	4	1/8	1/16
silt	4	8	1/16	1/256
clay	8		1/256	

The sandstone class of each data set, if available, is included in the index (Table 2) as well as in the descriptive files for each data set. Sandstone class, which is based upon the relative proportions of detrital quartz, rock fragments, and feldspar, was either stated by the authors or else was inferred from analyses provided by the authors, in accordance with the ternary diagram of Figure 1.

Many data sets were taken from figures in the referenced papers and as a consequence depths are not available for individual samples in the digital files, whereas data sets taken from tables are usually listed with depths. On the other hand, a depth range is given in the text file for almost all data sets. It can be assumed that the sample depths lie within this depth range, which was taken from the text or a figure in the reference.

If an author indicated that a sample was fractured, then permeability and porosity data for that sample were not plotted. Without such notation, we had no way to discriminate fractured samples.

The Catalog

Each permeability-porosity data set has three components:

1. A file listing the authors, the reference, the authors' affiliation, the geologic age of the formation, location, well names, depth range, various geologic descriptions, production of oil or gas, core measurement conditions, and method of data entry. These files can be viewed in *pdf* format and can also be retrieved in rich text (*rtf)* format.

2. A plot of permeability (millidarcies) on a logarithmic scale versus porosity (percent) on a linear scale. The porosity scale always starts at zero. The permeability scale changes from plot to plot to accommodate the data. One decade (factor of ten) of permeability range corresponds to a porosity range of 10%, so that the apparent slope of different data sets can be easily compared on a log(permeability) vs. porosity basis. Plots are in *pdf* format.

3. A table of data in spreadsheet format giving the permeability and porosity values used in the plots, as well as petrographic and x-ray diffraction analyses provided by the authors. Each spreadsheet is available as a worksheet named Authors-Date.xls.

Discussion

Geologic ages of the data sets ranges from Devonian to Holocene. The Holocene sample set (data set number 52 in Tables 1 and 2) differs from all others in the methods of sample acquisition and measurement. Unconsolidated samples collected from beaches, dunes, and river bars represent the properties of newly deposited sands. As such, the position of these data sets on permeability-porosity plots (see plot for data set 52, labeled "Pryor, 1973") reveal the initial conditions for the subsequent formation of consolidated sandstones. On the other hand, geological age is not a good predictor of permeability and porosity. Although the geologically oldest rocks are all well consolidated, the complexities of diagenetic processes, rather than absolute age, determine the present-day distribution of permeability and porosity.

Quartz arenites are sandstones in which the detrital quartz content exceeds 95% of grain content. During diagenesis, quartz overgrowths form on quartz grains and the rock is cemented with quartz. Such rocks have good permeability even at porosity values less than 10 percent. In other words, quartz arenites are efficient in the sense that much of the pore space contributing to fluid flow. Data sets 7 and 11 are examples of quartz arenites in which quartz cementation produces data sets with high permeability at low porosity.

Several data sets include estimates of porosity from petrographic (point count) analysis of thin sections (see Y/N column labeled "Thin Section Porosity" in Table 2). Such estimates include the larger pore sizes and exclude the smaller pore sizes, so it is likely that point-count estimates of porosity more closely represent the pore-size population controlling permeability than do the helium-based estimates of porosity. The permeability-porosity plot for data set 70 illustrates both point-count and helium-based estimates of porosity.

Conglomerates and coarse-grained sandstones sometimes have permeability values greater than values found in medium and fine-grained sandstones of comparable porosity. Examples of high permeability patterns in conglomerates and coarse-grained samples can be found in data sets 3, 13, 31, 55, 57, 59, and 64.

The effect of grain size on porosity and permeability can be seen on many of the plots. In unconsolidated sands, grain size is highly correlated with pore-throat size and hence is highly correlated with permeability. However, as diagenesis progresses, the effect of grain size alone becomes attenuated as pores and pore throats are compacted and filled with secondary minerals. For these reasons, the symbols representing different grain sizes become mixed in the plots. Examples are data sets 2, 5, and 58.

The environment of deposition plays a role in the permeability-porosity signature of eolian sandstones (data sets 2, 37, 39, 50, 66). Higher permeability is preserved in dune deposits as opposed to non-dune deposits.

The preservation of porosity and permeability at depth is sometimes attributed to the presence of chlorite rims on grain surfaces. Data sets 6, 32, and 66 report chlorite occurring as rims and even as cements in samples in which permeability has been preferentially preserved. However, in another data set (36), chlorite cement appears in samples in which the permeability is preferentially reduced.

Fibrous illite reduces permeability more than most clay minerals because it extends into or bridges the pore space. Data sets 26, 28, and 66 illustrate the effect of illite on permeability and porosity.

As already stated, most measurements are made at room temperature and at low pressure (ambient) conditions. What then are the values of porosity and permeability at reservoir conditions? One data set (number 33 in Tables 1 and 2) contains measurements of porosity and permeability as a function of confining pressure, which ranges from 250 to 5500 psi. The values are tabulated in the spreadsheet for data set 33. Porosity at reservoir pressure ranges from 98% to 80% of porosity at ambient conditions. However, permeability varies much more than porosity as a function of confining pressure (see plot "effect of confining pressure" for data set 33). Samples with porosity greater than 14% show the least sensitivity to confining pressure, with permeability at reservoir pressure between 57% and 87% of permeability at ambient pressure. Samples with porosity less than 14% and initial permeability less than 0.4 md all have much higher sensitivity to confining pressure, with values of permeability at reservoir pressure declining to less than 10% of the ambient value.

Summary

Porosity and permeability data serve as standard indicators of reservoir quality in the oil and gas industry. A catalog of data sets allows an explorationist to select an appropriate analog if adequate geological descriptors such as depth, geologic age, location, and grain size are available. Carefully described, referenced data sets are also useful for studying the behavior of porosity and permeability in the subsurface. This catalog provides one such collection of referenced data. The user can access the catalog by browsing through the plots of data, by inspecting Table 1 for specific geographic locations or geologic formations, by inspecting Table 2 for a sandstone classification or tabulated attribute, or by sorting the digital equivalents of Tables 1 and 2.

References

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